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Distribution of Helical Properties of Solar Magnetic Fields *

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Abstract We summarize studies of helical properties of solar magnetic fields such as current helicity and twist of magnetic fields in solar active regions (ARs), that are observational tracers of the alpha-effect in the solar convective zone (SCZ). Information on their spatial distribution is obtained by analysis of systematic magnetographic observations of active regions taken at Huairou Solar Observing Station of National Astronomical Observatories of Chinese Academy of Sciences. The main property is that the tracers of the alpha-effect are antisymmetric about the solar equator. Identifying longitudinal migration of active regions with their *individual rotation rates* and taking into account the internal differential rotation law within the SCZ known from helioseismology, we deduce the distribution of the effect over depth. We have found evidence that the alpha-effect changes its value and sign near the bottom of the SCZ, and this is in accord with the theoretical studies and numerical simulations. We discuss other regularities which can be revealed by further analysis such as possible dependence on longitude, time, and magnetic field strength, etc.

Key words: Sun: activity — Sun: magnetic fields

1 INTRODUCTION

Studies of magnetic and current helicities, and twist of magnetic fields are very significant when seeking knowledge on the spatially-temporal distribution of the α-effect used in the mean-field dynamo theory (e.g. Seehafer 1990, 1994). Observationally available information on tracers of the this effect, such as $H_{\rm c}$ (current helicity density averaged over a given active region) and $\alpha_{\rm ff}$ (force-free field coefficient averaged over a given active region) are at present available from magnetographic observations. For the present study we used a series of systematic data taken

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at Huairou Solar Observing Station of National Astronomical Observatories of China. It is interesting to consider how these tracers vary with *a number of factors*, (1) **time**, (2) **latitude**, (3) **longitude** and how they depend on (4) the magnetic field strength **net flux**) and (5) partial (individual) differential **rotation rate** of the given AR (active region). If the net flux has not been calculated one may consider the areas covered by the spots in the active regions as given by the NOAA database. Below we shall examine these factors in detail.

First, we would like to summarize what are already known on the spatial-temporal distribution of the tracers of helicity and alpha-effect over the solar surface. We are going to consider these quantities and accumulate all observational tracers of the alpha-effect in the solar convective zone (SCZ). Before going further it is important to understand the role of the present studies with respect to what has already been done, and what is important for the further development.

(1) The average twist $\alpha_{\rm ff}$ changes very little with **time**. However, the current helicity $H_{\rm c}$, being proportional to some power of the magnetic field intensity, is somehow modulated by the solar cycle (Bao & Zhang 1998). In the fine structure of temporal variation of averaged $\alpha_{\rm ff}$ (Kuzanyan et al. 2000) we can find some features of the so-called semi-biennial (Benevolenskaya 1998, 2000) periodicity.

(2) There is evidence that the alpha-effect (or some of its tracers) is an odd function of the heliographic **latitude**, as suggested by theoretical studies of, e.g., Krause (1967). There are many papers indicating this fact (e.g., Seehafer 1990; Abramenko et al. 1996; Pevtsov & Canfield 1994, 1995; Longcope et al. 1998; Bao & Zhang 1998; Zhang & Bao 1999; Kuzanyan et al. 2000). Most of the active regions obey the so-called *hemispheric rule*, i.e. helicity vortices are mainly negative in the Northern hemisphere and positive in the Southern. It is interesting to note that the same rule is revealed in the kinetic helicity of turbulent plasma motion in the solar photosphere by analysis of helioseismological data (Duvall & Gizon 2000).

(3) Dependence on **longitude** is not reliably known yet. Some preliminary considerations of the longitudinal distributions of active regions (Zhang & Bao 1999) which violate the hemispheric rule may be interpreted as signature of active longitudes (cf. Vitinsky, Kopetsky, Kuklin 1986). However, this trend is rather weak and for statistical proof of such evidence we have to examine a much larger dataset of active regions (at least a few thousand while at the present time we have only a few hundred).

(4) There is a number of theoretical results concerning the dependence of the alpha-effect on **magnetic field strength** (e.g., Vainstein & Cataneo 1992; Brandendurg & Donner 1997; Blackman & Field, 2000a; Field et al. 1999). Some results contradict some others and there has been active discussion in this field (see, e.g., Blackman & Field 2000b). However, there is no observational evidence for any of such theoretical predictions as yet. It would be very challenging to consider such dependence. Some theories (e.g. Brandenburg & Donner 1997; Ossendrijver et al. 2001) suggested that for weak magnetic fields the alpha-effect should first increase with the field intensity, then reach some saturation level and then either increase slowly of even decrease.

So, in our forthcoming studies we shall consider the dependence of the tracers of the alpha-effect on the averaged magnetic field strength, i.e. **net flux**. Again, if the net flux has not been calculated we can use the areas covered by spots in active regions supplied by NOAA database. Unfortunately, the last quantity has a large scatter and we may have to use median values.

(5) So far, the dependence of the alpha-effect and its tracers such as mean kinetic and current helicities on depth was studied only theoretically. Estimates based on Krause's (1967)

assumptions indicate that this quantity changes sign with depth, near the base of the convective zone (e.g., Krivodubsky 1998). Brummell et al. (1998) suggested that direct numerical simulations of kinetic helicity have shown the same dependence. The calculated dependence changed sign over depth near the bottom of the layer of stratification (i.e. the solar convective zone.) We expect the active regions over which the sign of H_c and α_{ff} disobeys the hemispheric rule to be localized mainly near the bottom of the convective zone, i.e., in larger part they keep the properties of the flow at the bottom of the convective zone. This property is very important for some dynamo models (e.g., Belvedere et al. 2000) as it supports the idea of an overshoot layer near the base of the convection zone. In this paper we attempt to approach this problem using a large sample of observationally available magnetograms of solar active regions. We sort them by the differential rotation of their structures, and so, effectively, provide the internal rotation law in the solar convective zone by the depth of the flow beneath them.

The objective of this paper is to summarize all of the knowledge on the spatial-temporal distribution of the observational tracers of the alpha-effect in the solar convective zone and acquire some additional information of its fine structure by the use of a large, and growing dataset of available observations.

2 LOOKING INTO THE DEEP SOLAR INTERIOR: OUR APPROACH

Recent helioseismological inversions (e.g., Schou et al. 1998) yielded rather precise data on the solar internal rotation. As its approximation by analytic fitting function $\Omega(r, \theta)$ (Belvedere et al. 2000) shows, it grows with radius at least between 0.67 and 0.93 solar radii for a rather wide range of latitudes. We will examine every active region with a certain "effective" latitude $\theta_{\rm AR}$ and depth $r_{\rm AR}$ within these ranges (under the assumption that ARs arise from rather deep part of the convective zone). Then, taking into account of a partial drift of the given active region over the Carrington heliographic longitude over a few days of the available observations, we can find (at least for some active regions of our dataset) their individual rotation rate $\Omega_{\rm AR}$. Then with $\theta_{\rm AR}$ we invert the function of internal solar rotation rate $\Omega(r, \theta)$ and estimate its "effective" depth $r_{\rm AR}$. Here we may neglect the effect of the poleward inclination of the rising flux tubes described by Schüssler et al. (1996) which may lead to the active region having its "root" in a somewhat lower latitude.

The key newest concept of the present study is *partial (individual) rotation rate* for the given active region. The NOAA data enable one to reveal correlation with time (over several years) of the longitudinal location of the centre of the active region for a number of active regions (a few thousand since 1983). Preliminary studies have shown that for at least 20%–30% of the active regions the correlation coefficient between longitude and time is quite high at around 0.6–0.7. For such active regions (numbering several hundreds) we can calculate the rotation rate and assign an *"effective" depth* to each. So, we can now consider the variation of tracers like spot area with this "effective" depth. In forthcoming papers we will check how the distribution of active regions in this depth range changes with time, i.e., the phase of the solar cycle.

We would like to stress again, that the method developed in this paper is based on the difference between the *partial (individual) rotation rate* of active regions and the average rotation rate of the media within the solar convective zone at a given latitude. In relatively low latitudes, where the internal rotation rate is known from helioseismological studies as a function of the latitude and depth, we can estimate the value of depth at which this rotation rate is likely to be close to the *individual rotation rate* of the given active region. Though this rotation rate is not well defined for many active regions, we can still calculate it for a large sample, and sort them into at least three layers within the SCZ: a deep-seated slow rotating layer, a middle layer, and a shallow-seated fast rotating layer. It is notable that this *"effective" depth* $r_{\rm AR}$ is not the depth of some particular structure of the sunspot or sunspot group, rather, it is an effective depth at which the rotation rate of the flow within the solar convective zone corresponds to the rotation rate of the entire active region structure. Moreover, we define no location of active region structures, but some effective depth of the flow beneath of the active region.

However, some preliminary studies showed that a certain fraction of active regions have individual rotation rates faster than the mean internal rotation of the solar convective zone at any depth for the given latitude. Apart from the influence of inaccuracy in observations and calculations of the rotation rate, this fact can be attributed to the effect of the poleward drift of rising flux tubes in a rotating convection zone (e.g., Schüssler et al. 1996). Under the assumption that such *a "superfast rotating" active region* arises from the fastest rotating depth (approximately 0.93 of solar radius units for a rather wide range of latitudes) it is possible to find the shift in latitude between its actual position and *the "effective" latitude* at which the rotation rate of the active region corresponds to the fastest rotating depth 0.93. We are planning to carry out studies of such "superfast rotating" ARs in a forthcoming paper.

3 HEMISPHERIC SIGN RULE VERSUS ROTATION

We have collected a time series of current helicity density and twist for a sample of 410 active regions obtained from analysis of magnetograms taken at Huairou Solar Observing Station of Beijing Astronomical Observatory in the nine years 1988–1996. This is a part of the data used in previous studies (e.g., Bao & Zhang 1998; Zhang & Bao 1998; Kuzanyan et al. 2000; Zhang et al. 2000). For every given active region we retrieved all the entries from NOAA database on active regions (ftp://ftp.ngdc.noaa.gov /STP/SOLAR_DATA/SUNSPOT _REGIONS/USAF_MWL/) within 3 days before and after the date of the Huairou magnetograms. In many cases there are a few tens of such data points. For these data points we tried to uncover any trend in longitudinal migration of the center of an active region. We realize that the structure of an active region changes with time and the location of the center may have a lot of excursions. For some of these active regions we could find a certain time dependence of the Carrington heliographic longitude. As a typical example, we plot in Fig. 1 the NOAA data for AR 4983 (central meridian pass on 1988 April 13). There, the correlation coefficient is –0.53. Furthermore, at 2σ level of accuracy for 178 active regions (43% of total 410 ARs) we found such a trend with a correlation coefficient greater than 0.5 and for 134 regions (33% of total 410 ARs), one greater than 0.6 (for latitudes up to $\pm 31^\circ$). We selected these for further analysis and calculated their *Individual Rotation Rates*.

Then we examined the data of internal differential rotation of the SCZ based on SOHO-MDI results (e.g., Schou et al. 1998). We acknowledge the kind permission of Alexander Kosovichev to use the the solar internal rotation rate data (http://quake.stanford.edu/ sasha/omega.dat). To minimize the influence of errors in the calculation of this observational dependence we used the analytic fitting function $\Omega(r,\theta)$ for this quantity developed by Belvedere et al. (2000)

$$\Omega(r,\theta) = \sum_{j=0}^{2} \cos 2j\theta \sum_{i=0}^{4} c_{i,j} r^i \ , \qquad (1)$$

$$(0 \le \theta \le 75^\circ, \ \ 0.65 \le \frac{r}{R} \le 0.95)$$

where θ is latitude, r/R fractional radius, and the values of coefficients $c_{i,j}$ are given in Belvedere et al. (2000). It is also stated there that the rms deviation for the analytic approximation (1) is of order 0.8%.

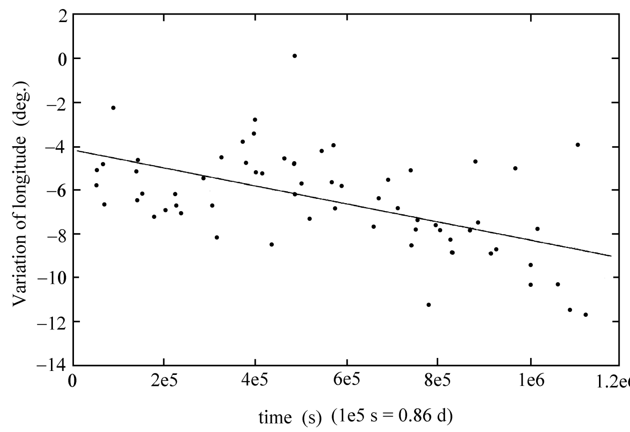

Fig. 1 An example showing relative migration of the center of AR 4983 in time. Average latitude $-31°$ (S31), Central Meridian Passage 1988 April 13. The correlation coefficient between the Carrington longitude and time is -0.53. The solid line indicates the best linear fit.

For a wide range of the rotation rate from the equator to at least 31° we note that the internal rotation rate increases with radius up to approximately $r = 0.93$ solar radii (see, e.g., Schou et al. 1998). So, our assumption is that the "root" of active regions, or the depth they arise from is below this level. We assume that the main mechanism of the solar dynamo action is concentrated near the base of the convection zone in the so-called overshoot (or generation) layer. The magnetic flux tubes arise from this depth and pass through the higher zone where the properties of convection could be different from the lower zone, although due to the large scales of the magnetic field and the low diffusion coefficient, the field is frozen into the plasma and the motion retains some properties of the generation layer.

On the basis of the smooth analytic fit (Belvedere et al. 2000) we calculated the rotation rate versus latitude curve for depths 0.68, 0.76, 0.84 and 0.93 solar radii. These correspond to the boundaries of the three layers: the slow rotating deep layer at 0.68–0.76, the middle layer at 0.76–0.84 and the fast rotating shallow layer at 0.84–0.93. The layer lying above 0.93 rotates slower than at 0.93, and we ignore it. Rotation rates of these layers calculated by Eq. (1) are shown in Fig. 2. Their analytic expressions are also given below (theta latitude).

```
r=0.68  438.303-5.32385*cos[2*theta]+ 2.70985*cos[4*theta]
r < 0.72                                in this range 75 ARs (42% of 178)
r=0.72  424.057+25.4841*cos[2*theta]+5.70533*cos[4*theta]
0.72 < r < 0.80                         in this range 10 ARs (6% of 178)
r=0.80  410.782+51.0547*cos[2*theta]+2.11298*cos[4*theta]
r > 0.80                                in this range 93 ARs (52% of 178)
r=0.93  407.678+70.1250*cos[2*theta]-10.0472*cos[4*theta]
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Now, we consider the distribution of the active regions over these layers. We take only the ARs with Carrington longitude - time correlation coefficients greater than 0.5 and calculate their *Individual Rotation Rates*. There are 178 such ARs in total in our sample. Using the formulae above we sort them into groups with faster or slower rotation rates, i.e., the different layers. They are approximately equally distributed in the upper and lower layers (42% and 52%), with very few in the middle layer (6%).

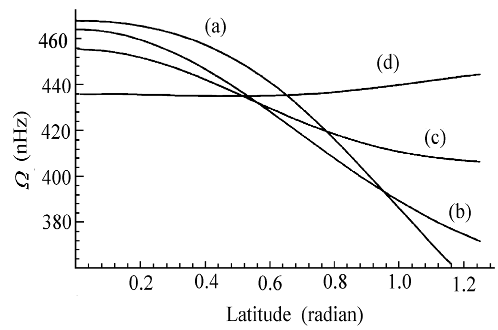

Fig. 2 Variation of internal rotation rate in nHz with heliographic latitude $\Omega(r, \theta)$ in radian at depths $r = 0.68$ (a), 0.72 (b), 0.80 (c), 0.93 (d) solar radii.

We can see that there are a number of active regions where the individual rotation rate exceeds the fastest rotation rate for the given latitude (corresponding to approximately $r = 0.93$) and also many where the rotation rate falls below the slowest assumed for a convective zone at $r = 0.68$. Apart from the influence of inaccuracy in observational data and of the high dispersion of the data points on longitudinal evolution for the calculation of the rotation rate, this fact can be attributed to the effect of the poleward inclination of arising flux tubes in a rotating convection zone (e.g., Schüssler et al. 1996). However, for the sake of simplicity we identified such super-slow and super-fast regions with the deep and shallow layers. There are very few active regions in the middle layer and we may omit them in further consideration.

The hemispheric rule discussed above reveals that most of the active regions in the northern/southern hemisphere have negative/positive sign of average current helicity density H_c (82%) and twist α_{ff} (68%). These figures refer to a sample of 410 magnetograms, which is a part of what was calculated by Bao & Zhang (1998). The active regions for which the hemispheric helicity rule is violated are of particular interest to us. For a total of 410 active regions there are 75 (or 18%) such regions with respect to the current helicity density H_c, and 132 (32%) such regions with respect to the twist, i.e., force-free coefficient α_{ff}. Now using the method of determination of *individual rotation rates* of ARs, we consider the distribution of the active regions violating the hemispheric rule over different layers of the SCZ. The results are given in Table 1.

It is very important to note that the number of active regions for which the hemispheric rule is disobeyed with respect to the current helicity density H_c, is very different for the deep and shallow layers (see Table 1): while the total fraction of such active regions over all 410 ARs in the whole sample is 18%, the fraction of such active regions is 27% for the deep layer and 6% for the shallow layer. On the other hand, the number of active regions for which the hemispheric rule is violated with respect to α_{ff}, is more or less the same for the deep (29%) and shallow layers (36%), (the fraction for the whole is 32%). While these figures are based on a limited number of active regions, the trends they reveal are definitely statistically significant. We attribute the disproportion found here to the important role of turbulence within the convection zone.

Table 1 Distribution of Active Regions with Sign of H_c and α_{ff} Violating the Hemispheric Rule

	TOTAL ARs violating the hemispheric rule over total sampling	SELECTED ARs with rotation rate determined with correlation higher $r_{2\sigma} > 0.5$	DEEP rotation slower than level $r = 0.72$ (42% of ARs)	MIDDLE between (6% of ARs)	SHALLOW rotation faster than level $r = 0.80$ (52% of ARs)
α_{ff}	132/410=32%	60/178=34%	22/75=29%	5/10	33/93=36%
H_c	75/410=18%	28/178=16%	20/75=27%	2/10	**6**/93=**6**%

Note: Bottom right: an important result is shown bold.

4 DISCUSSION

Thus, we see that most of the active regions for which the hemispheric helicity rule is violated with respect to the current helicity density H_c, are located in the deeper part of the SCZ. This result can be interpreted as an indication that the alpha-effect and its tracer, the current helicity density H_c, change signs at a large depth of the SCZ. This is in agreement with the spatial properties of these quantities estimated in the theoretical (e.g., Krause 1967; Krivodubsky 1998) and numerical (Brummell et al. 1998) studies. Indeed, the kinetic and current helicities, as well as the α-effect should change their signs near the bottom of the convection zone, due to the dominance of divergent/convergent flows in the lower/upper part of the convection zone. This supports the simple but robust models of the solar magnetic activity developed in the framework of asymptotic WKB solution of the mean-field dynamo equations (Ruzmaikin & Starchenko 1987; Makarov et al. 1987; Kuzanyan & Sokoloff 1995, 1997; Belvedere et al. 2000). When more observational data with more vector magnetograms of active regions over longer periods of time are available, these properties can be examined in greater detail and more accurately.

We must note that the results above are somehow affected by imperfections in the observational technique and instruments. The impact of magneto-optical effects (Faraday rotation) on the determination of the transverse fields also requires further studies. However, recent comparison of the results obtained in different observatories including Huairou (cf. Mees) shows no statistically significant difference between the different data samples (see, e.g., Bao et al. 2000). Nevertheless, the methods of determination of the transverse magnetic fields could be improved by further development of the instruments and observational methods. The analysis of the raw data did not take into account some fine effects like the effect of projection of an active region to the plane at which we observe magnetic fields; this effect is small, because most of the active regions are observed near the solar equator and near the central meridian.

All these issues might be corrected by further improvement of observational technique and analysis of data. Nevertheless, we believe, that the significance and theoretical meanings of the data are the same as we itemized in this paper.

5 CONCLUSIONS

We have found an observational piece of evidence that current helicity density H_c as a tracer of the α-effect likely changes its sign with depth near the bottom of the solar convective zone.

Further challenging studies we are planning to undertake are the following:

1) Studies of dependence of H_c and α_{ff} vs. Net Flux and vs. Spot coverage Area, we expect the tracers of the alpha-effect to depend on these magnetic energy quantities.
2) Studies of dependence of the Hemispheric Sign Law versus H_c and α_{ff} on CDM (Central Meridian Distance). Revealing of Influence of the Projection Effect. This improves our belief in the reliability of the observational dataset.
3) Net Flux and Spot coverage Area vs. Rotation Rate, i.e. Depth. It is interesting to study this new subject directly, but not related to the twist and helicity problem. This is important in the studies of flux tube instability and magnetic energy transfer. Thus we will make further use of the technique of determination of partial rotation rates of Ars, developed in the present paper.
4) "Schüssler" Shift in Latitude. The phenomenon of "Superfast" and "Superslow" rotating active regions (cf. Schüssler et al. 1996) requires further studies. This is also important in understanding the mechanism of flux tube arising from the bottom to the top of the Solar Convective Zone.

6 SUMMARY ON THE DISTRIBUTION OF HELICAL PROPERTIES OF SOLAR MAGNETIC FIELDS

The studies above reveal the following properties of the spatial and temporal distribution of H_c and α_{ff}:

(1) *time*: No distinct variation for α_{ff} over the solar cycle though there are possible semi-biennial changes (Kuzanyan et al. 2000), variation of H_c with magnetic field intensity, e.g., Wolf Number (Bao & Zhang 1998). The signs of H_c and α_{ff} in a given hemisphere do not change over the solar cycles.
(2) *latitude*: Prominent latitudinal asymmetry over the equator: odd functions of latitude $H_c(\theta)$ and $\alpha_{ff}(\theta)$, the hemispheric sign change law.
(3) *longitude*: Possible signatures of active longitudes, non-axisymmetric modes $m = 1, 2, \ldots$. This requires further studies on larger statistical data samplings.
(4) *strength of the magnetic field (averaged net flux)* or *spot coverage*: no clear trends found, yet studied insufficiently.
(5) *partial (individual) differential rotation rate of a given active region (AR),* i.e., *DEPTH*: Active regions with the wrong sign of H_c are likely more deep-seated (slower rotation) rather than shallow-seated => the function $H_c(r)$ likely changes sign near the bottom of the convective zone.

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